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14. ABSTRACT

Since early in the development of aerodynamic computational tools, when complex aircraft configurations could for the first time be accurately represented, the Holy Grail of the CFD community became predicting the trajectory of a store from an aircraft. However, the participants could never agree on either what would constitute a successful prediction, or what computational approach should be used. Many claimed that store separation was an unsteady phenomenon, and that the solutions would have to be done in a time dependent manner (this despite the multitude of evidence to the contrary, where quasi-steady wind tunnel simulations in almost all cases have shown excellent agreement with the flight test results).

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GRID BASED APPROACH TO STORE SEPARATION

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ABSTRACT

Since early in the development of aerodynamic computational tools, when complex aircraft configurations could for the first time be accurately represented, the Holy Grail of the CFD community became predicting the trajectory of a store from an aircraft. However, the participants could never agree on either what would constitute a successful prediction, or what computational approach should be used. Many claimed that store separation was an unsteady phenomenon, and that the solutions would have to be done in a time dependent manner (this despite the multitude of evidence to the contrary, where quasi-steady wind tunnel simulations in almost all cases have shown excellent agreement with the flight test results).

Although a time dependent calculation is prohibitively expensive in terms of time and resources, CFD has shown the ability to accurately predict store loads at carriage for complex configurations at transonic speeds. A systematic approach, combining these carriage load predictions with an estimate of the aircraft induced incremental aerodynamic loads might give the best overall prediction at a minimum of time and effort expended. The authors will demonstrate how incremental wind tunnel grid data for one store can be used to provide excellent predictions for a store of similar shape (although with substantial differences in freestream characteristics).

NOMENCLATURE

BL: Aircraft Buttline, positive outboard, in.
C_l: Rolling moment coefficient, positive right wing down
C_m: Pitching moment coefficient, positive nose up
C_N: Normal Force coefficient, positive up
C_n: Yawing moment coefficient, positive nose right
C_Y: Side force coefficient, positive right
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
P: Store roll rate, positive rt wing down
Q: Store pitch rate, positive nose up
R: Store yaw rate, positive nose right
PHI: ϕ, Store roll angle, positive rt wing down, deg.
PSI: ψ, Store yaw angle, positive nose right, deg.
THE: θ, Store pitch angle, positive nose up, deg.
WL: Aircraft Waterline, positive up, in.
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
Note: all wind tunnel data were for right wing, flight test left (negative ϕ, ψ, Y)

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BACKGROUND

Any time a new aircraft is introduced, or an old aircraft undergoes substantial modifications or needs to be cleared for new stores, the store separation engineer is faced with a decision about how much effort will be required to grant a flight clearance. Generally, there are three approaches that can be used: similarity (also known as the hit-or-miss method), grid testing or Computational Aerodynamics.

In the early days, store separation was conducted in a hit or miss fashion - the stores would be dropped from the aircraft at gradually increasing speeds until the store came closer to or sometimes actually hit the aircraft. In some cases, this led to loss of aircraft, and had made test pilots reluctant to participate in store separation flight test programs.

During the 1960's, the Captive Trajectory System [1] (CTS) or grid testing method for store separation wind tunnel testing was developed. The CTS provided a considerable improvement over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight-testing. This procedure generally involves testing the store to determine it's freestream characteristics and then at various grid (X,Y, Z) locations underneath the aircraft to determine the aircraft flowfield effect at two or more store attitudes (ψ,θ,ϕ). Wind tunnel aerodynamic loads and moments are tabulated for each location in this grid. A six-degree-of-freedom trajectory program is then run off-line utilizing the freestream data and incremental grid data (the freestream aerodynamic load at the store attitude in the original grid subtracted out) interpolated for the store attitude at each time step to determine the store's trajectory. The advantage of this approach is that for one set of grid data (i.e. Mach, A/C configuration and angle of attack) numerous trajectories can be run examining the effects of store mass properties, ejector force characteristics and initial carriage loads. This is the standard method used by the U.S. Navy for any new aircraft/weapon configurations, and has demonstrated excellent[2] correlation with flight test results. The disadvantage of this approach is that it often requires considerable expenses in wind tunnel test time and resources (i.e. 6 months and $200-$500K) to be implemented.

Recently, Computational Aerodynamics, under the auspices of the ACFD[3,4] program, has demonstrated the ability to predict store trajectories at transonic speeds. However, full CFD solutions (time accurate Navier-Stokes) require resources comparable to the wind tunnel. One approach used by several participants[5,6,7] in the last ACFD Challenge was to use the computed aircraft flow field, in conjunction with an estimate of it's influence on the store aerodynamics, to calculate the decay of the carriage loads as the store moves away. Time accurate solutions[8, 9] required considerably more time and resources, with no appreciable improvement in the prediction accuracy.

What the present authors propose would perhaps allow for a better approximation of the aircraft flow field effect. It is assumed that the store aerodynamic load at any position in the grid is a function of its freestream aerodynamics and the aircraft induced aerodynamics at that flow field position. The freestream aerodynamics are a property of the store alone; the aircraft induced aerodynamics are mostly determined by the aircraft flowfield, with the mutual interference between the aircraft and store playing a secondary role. What is proposed is an extension of the grid method; i.e. incremental grid data for one store would be used in conjunction with freestream data of another store to predict that store's trajectory. Although others may have tried this approach, we propose to do this in a systematic fashion.

The U.S. Navy has extensive sets of grid and flight test trajectory data for the JDAM MK-83 and JDAM MK-84 stores, as well as flight test data for the original MK-83 and MK-84 stores which the JDAM derivative replaced. The JDAM grid data, in conjunction with MK-83 and MK-84 freestream data, will be used to predict MK-83 and MK-84 trajectories. The metrics for success will be to see if using incremental grid data for another store can give results comparable to those produced by CFD[4] for the MK-84 JDAM store.

MK-84LD/JDAM Freestream and Trajectory Test Data

Freestream, grid and F-18C trajectory flight test data were available for the MK-83 and MK-84 JDAM stores. Freestream and trajectory data were also available for the MK-84LD store separating from the F-18C aircraft. As may be seen in Figure 1, the normal force for the MK-83LD and the JDAM variant is almost identical at lower angles of attack. The pitching moment, however, is substantially different, Figure 2. The MK-84 characteristics are essentially the same, Figures 3 and 4.

When the MK-84 JDAM freestream and grid test data were input into a six degree of freedom program, an excellent match with F-18C flight test trajectory data from the inboard pylon at M = 0.94 at 4315 ft. were achieved, Figures 5 and 6. For store clearance purposes, the pitch and yaw behavior of the store for the first 250ms are of primary importance, since that is the time period when the store is close to the aircraft and may

cause a collision. The degradation of the pitch prediction after 20ms is not unexpected, since store grid data is only taken to +/-20 degrees in pitch and yaw attitudes, and store attitudes in excess of 20 degrees are rarely well predicted.

The MK-84 JDAM grid data were then input in the six degree of freedom program with MK-84LD freestream data, in an attempt to match F-18C flight test data at M = 0.97 and 11,180 ft in a 45^0 dive. As may be seen in Figures 7 and 8, the trajectory prediction for this case is in better agreement with the test data than was seen for the JDAM trajectory. Although this seems to be counterintuitive, particularly as the carriage loads (where the aircraft/store mutual interference is known to be the greatest) were arrived at directly by imposing the MK-84LD freestream data on the MK-84 JDAM grid data at carriage. One possible explanation for the excellent agreement is that the store in this case pitched down only 15 degrees, which was well within the store attitude grid data that were taken. Another consideration may be explained by the differences in freestream data seen in Figure 4. The MK-84LD moment data are linear, whereas, the MK-84 JDAM moment data are substantially non-linear, even changing from stable to unstable at angles of attack α between 10 and 15 deg. Since the trajectory code adds the flowfield increment to the freestream increment, it is anticipated that MK-84LD predicted trajectories should in most cases be in better agreement with flight test data than those for the JDAM variant.

The small discrepancy in yaw attitude, Figure 8, is probably due to an improper estimate of the carriage yawing moment. Once CFD calculations for this case are available, a better match with the test data is expected.

No other MK-84LD trajectory data for the same aircraft configuration were available. However, extensive trajectory data from the inboard pylon next to the TFLIR were available. Since the purpose of this study is to validate the approach of using grid data for one store to predict trajectories for similar stores, it is assumed that incremental CFD data for aircraft configuration effects will be available in the future. At this time, empirical corrections to the C_m and C_n will be applied to see if a trajectory match can be achieved.

Wind tunnel grid data for the MK-83 JDAM store exhibited significant changes in the store's Cm and Cn characteristics, particularly for M > 0.90. As a first step, Cn and Cm increments of 0.4 and –0.4 were added to the MK-84 JDAM grid data. These modified MK-84 JDAM grid data were then input in the six degree of freedom program with MK-84LD freestream data, in an attempt to match F-18C flight test data at M = 0.9 and 10,350 ft in a 45^0 dive. As may be seen in Figures 9 and 10, the trajectory prediction for this case is in excellent agreement with the flight test data (the yaw prediction was shifted by -0.9 degrees to account for the obvious discrepancy in the photogrametrics test data).

Using the same approach, an attempt was made to match F-18C flight test data at M = 0.93 and 10,470 ft in a 60^0 dive. In this case, Cn and Cm increments of 0.7 and –0.7 were added to the MK-84 JDAM grid data. As may be seen in Figures 11 and 12, the trajectory predictions for this case are again in excellent agreement with the flight test data (the yaw prediction was again shifted by -0.9 degrees to account for the obvious discrepancy in the photogrametrics test data). An excellent match was also obtained with the flight test data at M = 0.96 and 11,250 ft in a 45^0 dive, Figures 13 and 14, when Cn and Cm increments of 1.0 and –1.0 were added to the MK-84 JDAM grid data (the yaw prediction was again shifted).

Since no wind tunnel data were available, the pitching and yawing moment increments were arbitrarily added to the JDAM grid data in an attempt to account for the TFLIR effect on the aircraft flowfield. The increments (0.4, 0.7 and 1.0) were selected on the basis of providing the best match with the flight test results. Obviously, that approach can not be used in a new aircraft/store certification program. However, if CFD can validate that these increments are due to the TFLIR aerodynamic effect on the aircraft flowfield, then the grid based approach described will have proven it's utility. A systematic wind tunnel and CFD effort to understand and predict the TFLIR effect is ongoing.

CONCLUSIONS

Does that mean that we can throw away the wind tunnel, and just use the MK-84 JDAM grid data for any future store trajectories from the F-18C aircraft? Unfortunately, it's not that simple. Although the freestream data for the MK-84LD and the JDAM version were dramatically different, the stores were geometrically identical, except for the presence of strakes on the JDAM variant. Obviously, the more the stores differ geometrically, the less use can be made of one store's grid data to make trajectory predictions for another. As may be seen in Figures 15 and 16, grid data for the MK-83 JDAM and the MK-84 JDAM show as much difference from each other as can be attributed to aircraft flow field effects. Clearly, there's a limit to the utility of dissimilar grid data.

However, many stores have similar geometric properties for several variants (i.e. MK-82LD, MK-82HD, MK-82 Snakeye). Grid data for one store, combined with freestream data for the other variants, may be all that is needed to clear all of the different variants.

Further study of this approach is needed. One obvious application will be the recently the Technical Cooperative Program (TTCP) Group WPN-2 organized a new Key Technical Area (KTA) 2-18. Although this KTA has only been recently approved by WPN Group, significant quantities of experimental data have already been gathered, reviewed and organized in preparation for experimental data-to-CFD prediction comparisons. The large wind tunnel Pressure Sensitive Paint (PSP) data set and store captive loads data sets from NRC/IAR's high speed tunnel have been reviewed and the appropriate data is being prepared for use in comparative studies. To date, specific subsets of the PSP data for the CF-18/MK-83 test case have been provided to interested participants under the auspices of TTCP/KTA 2-18. It should be noted that the empirical data related specifically to the test case under analysis has intentionally not been released to participating countries to date. This comparative data will not be furnished until CFD computations have been completed, in an effort to demonstrate/evaluate the true capability of CFD in solving real world stores separation problems.

The MK-83 JDAM grid data will be used to make trajectory predictions for the MK-83LD bomb, prior to access to the Canadian MK-83 trajectory data. This should allow for a better evaluation of this approach.

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Normal Force

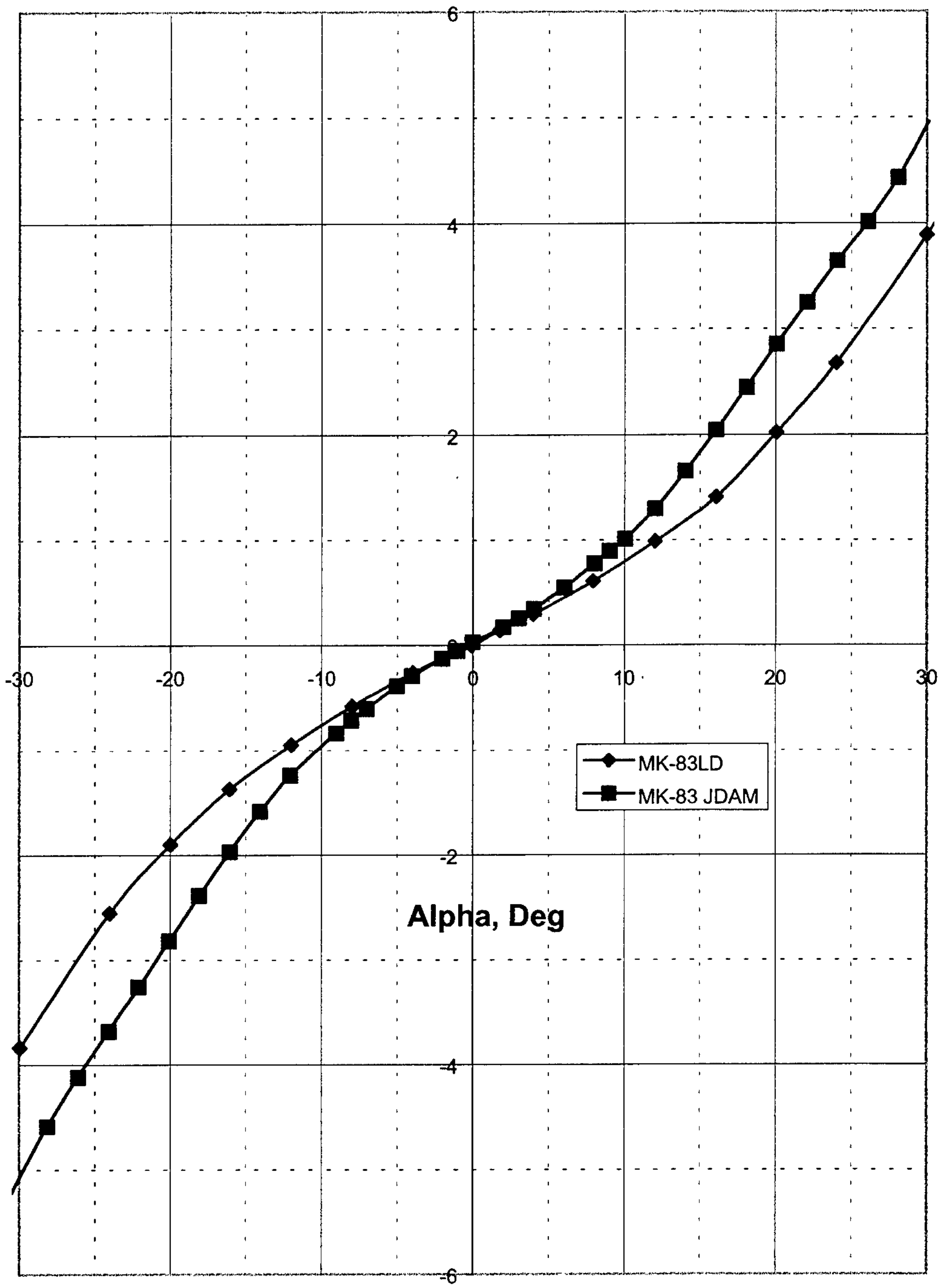


FIGURE 1

Pitching Moment

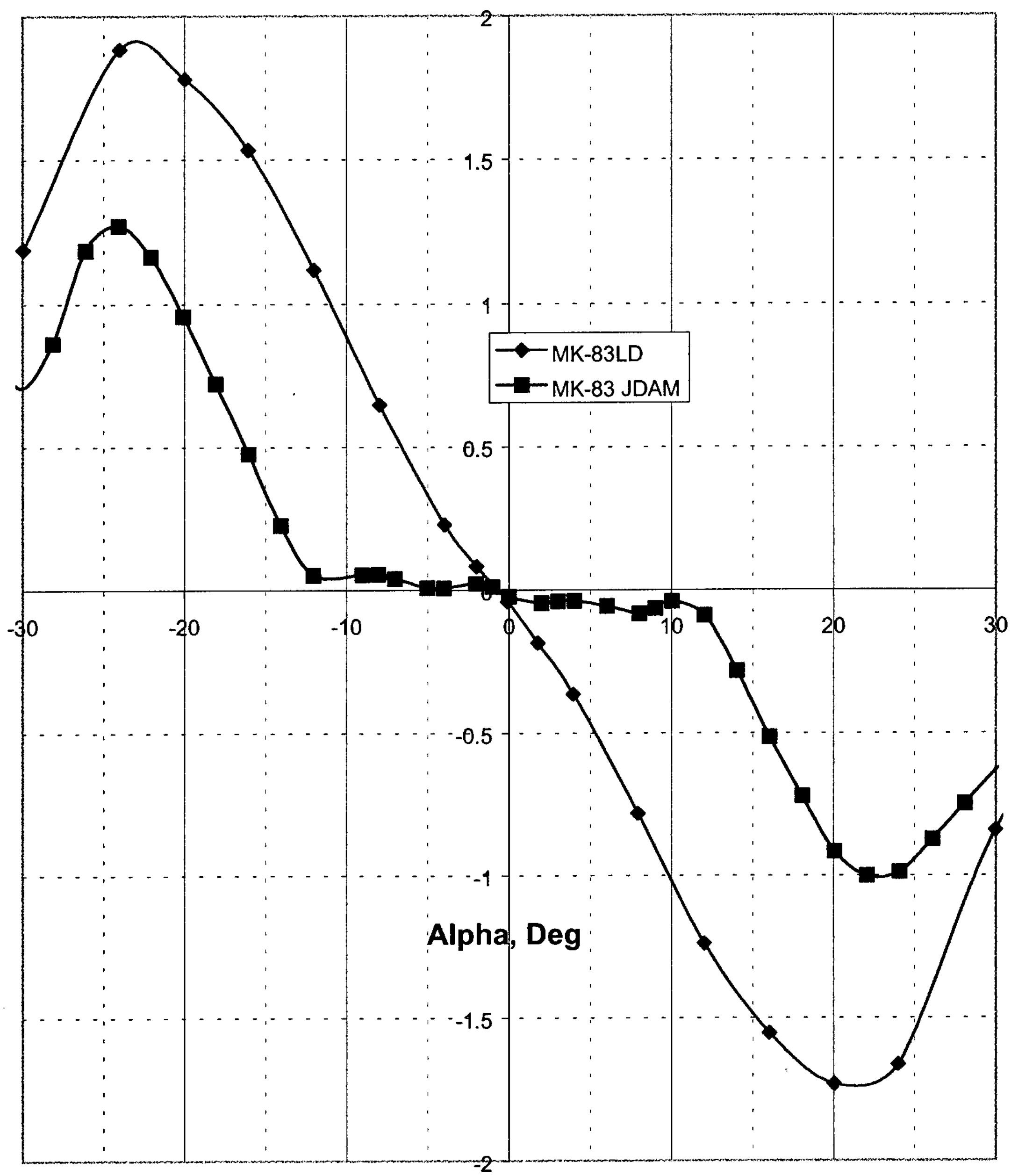
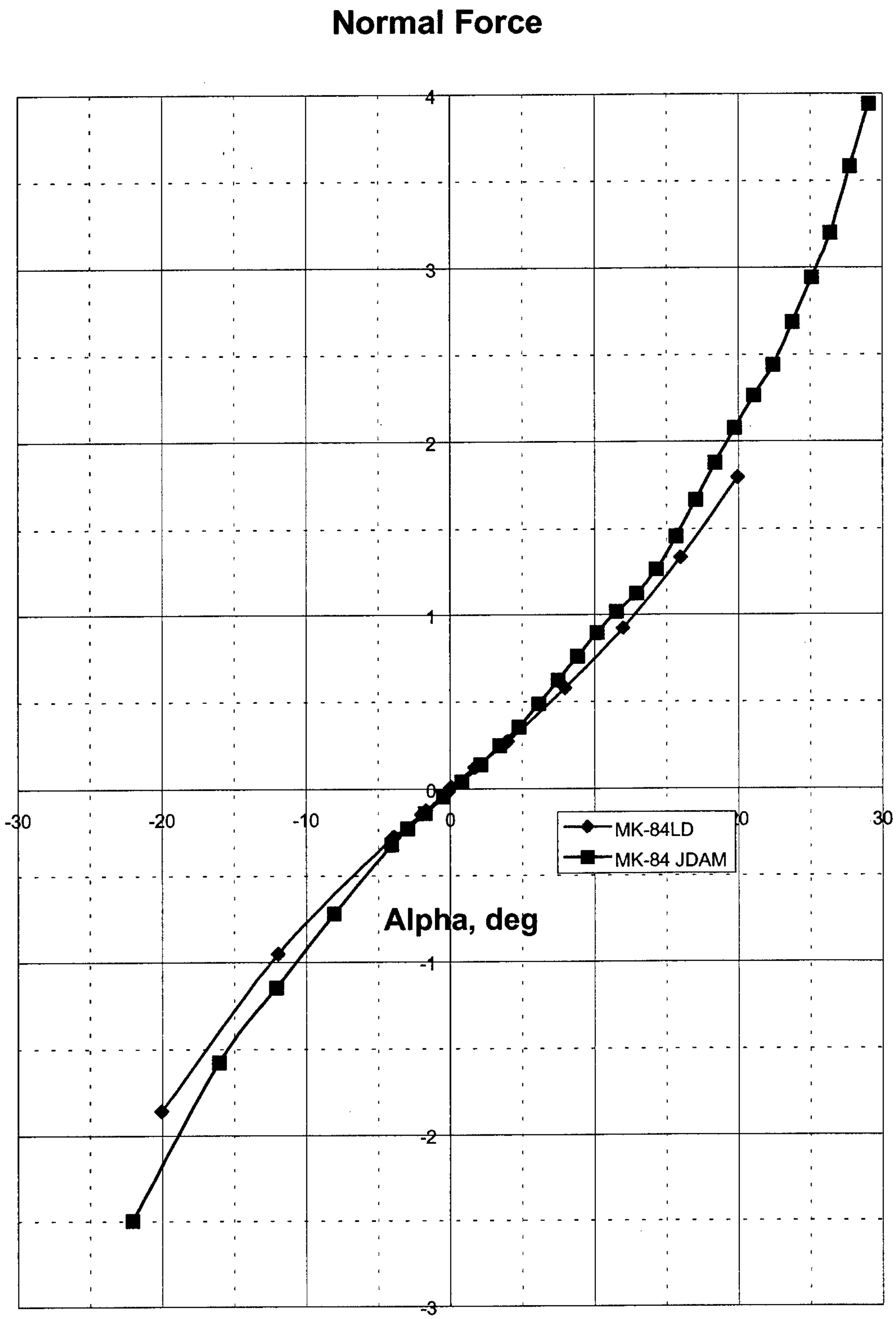


FIGURE 2



Normal Force
4
3
2
1
0
-1
-2
-3
-30
-20
-10
0
20
30
MK-84LD
MK-84 JDAM
Alpha, deg

FIGURE 3

Pitching Moment

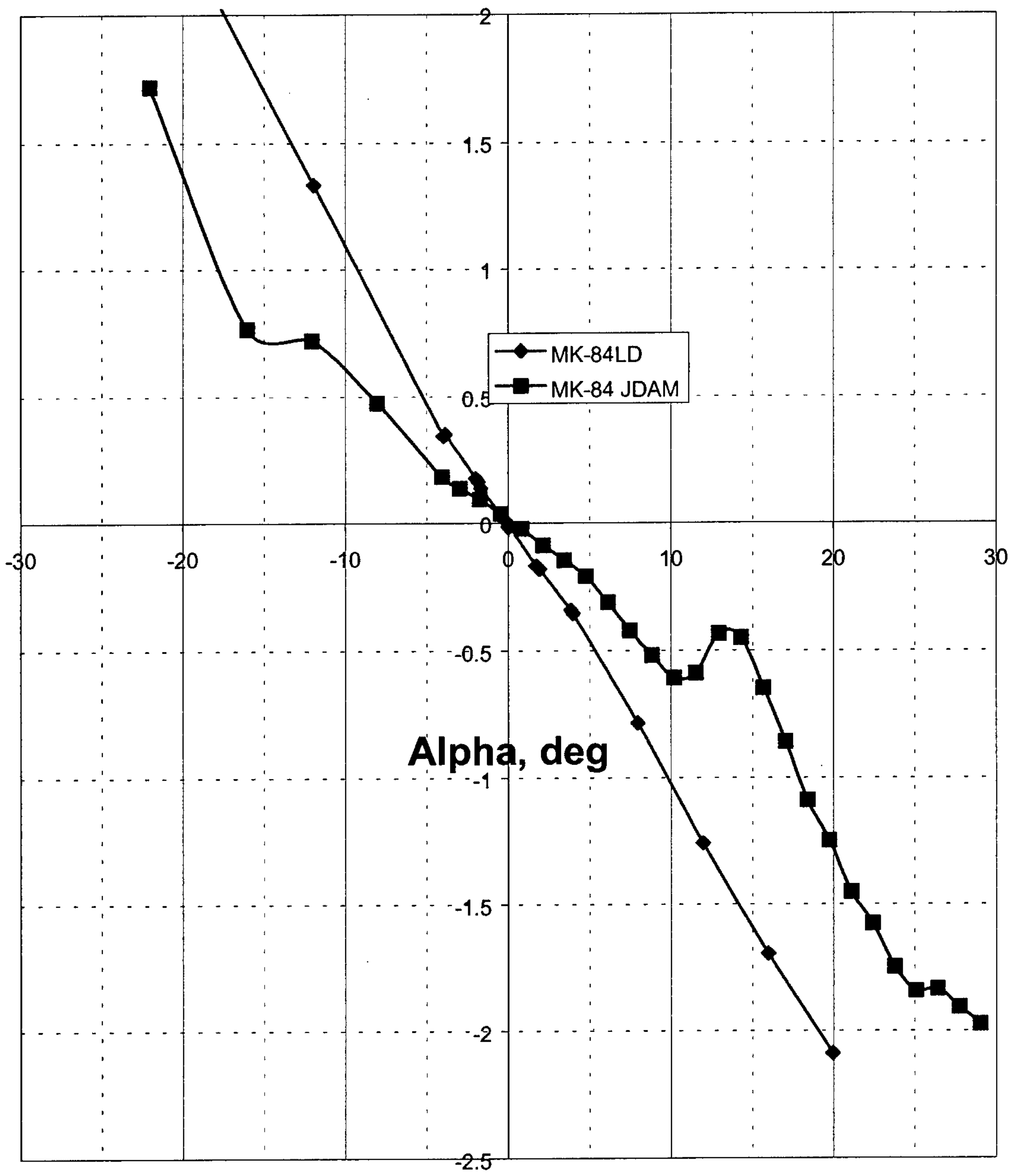


FIGURE 4

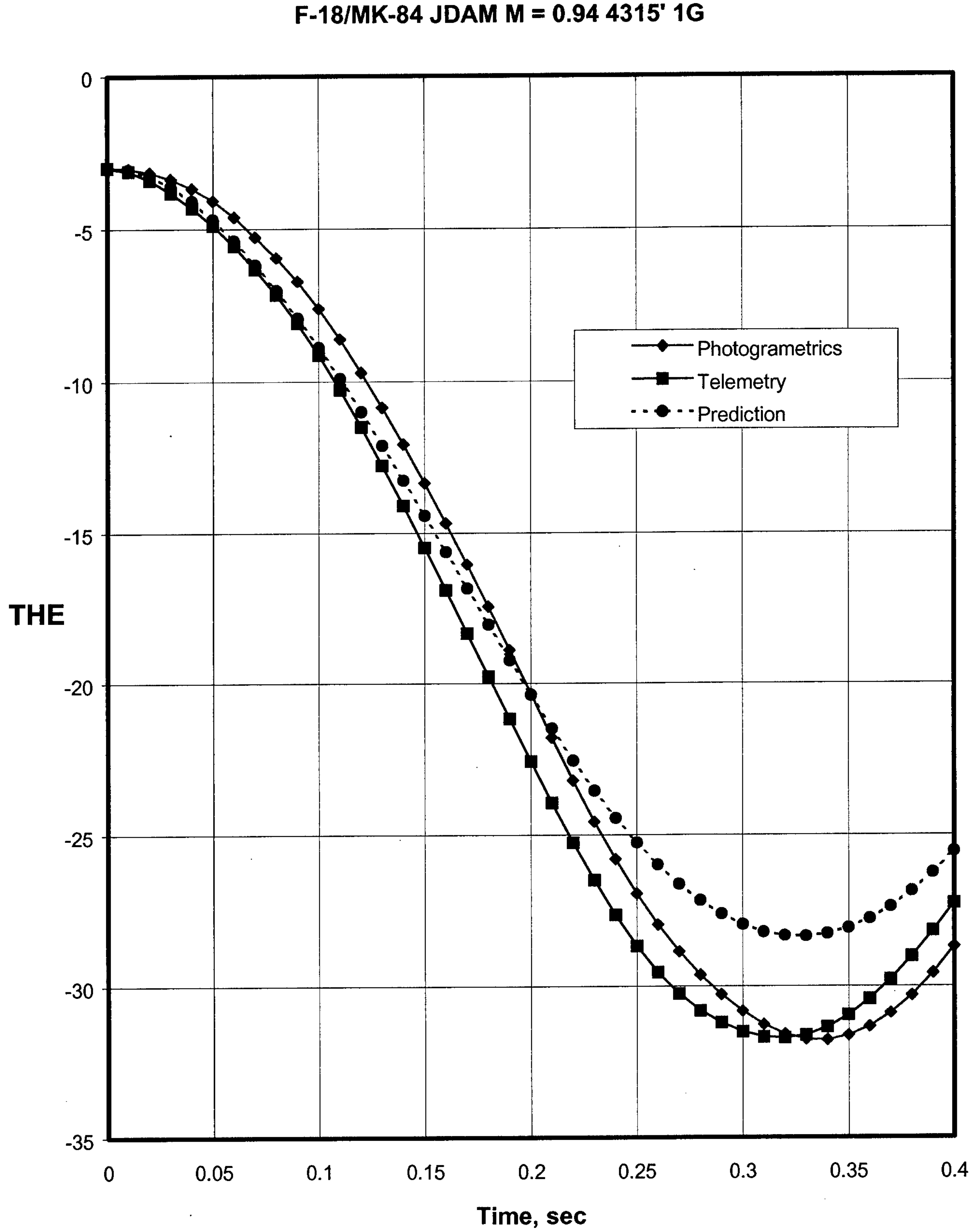

F-18/MK-84 JDAM M = 0.94 4315' 1G
THE
Time, sec
Photogrametrics
Telemetry
Prediction
0
-5
-10
-15
-20
-25
-30
-35
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

FIGURE 5

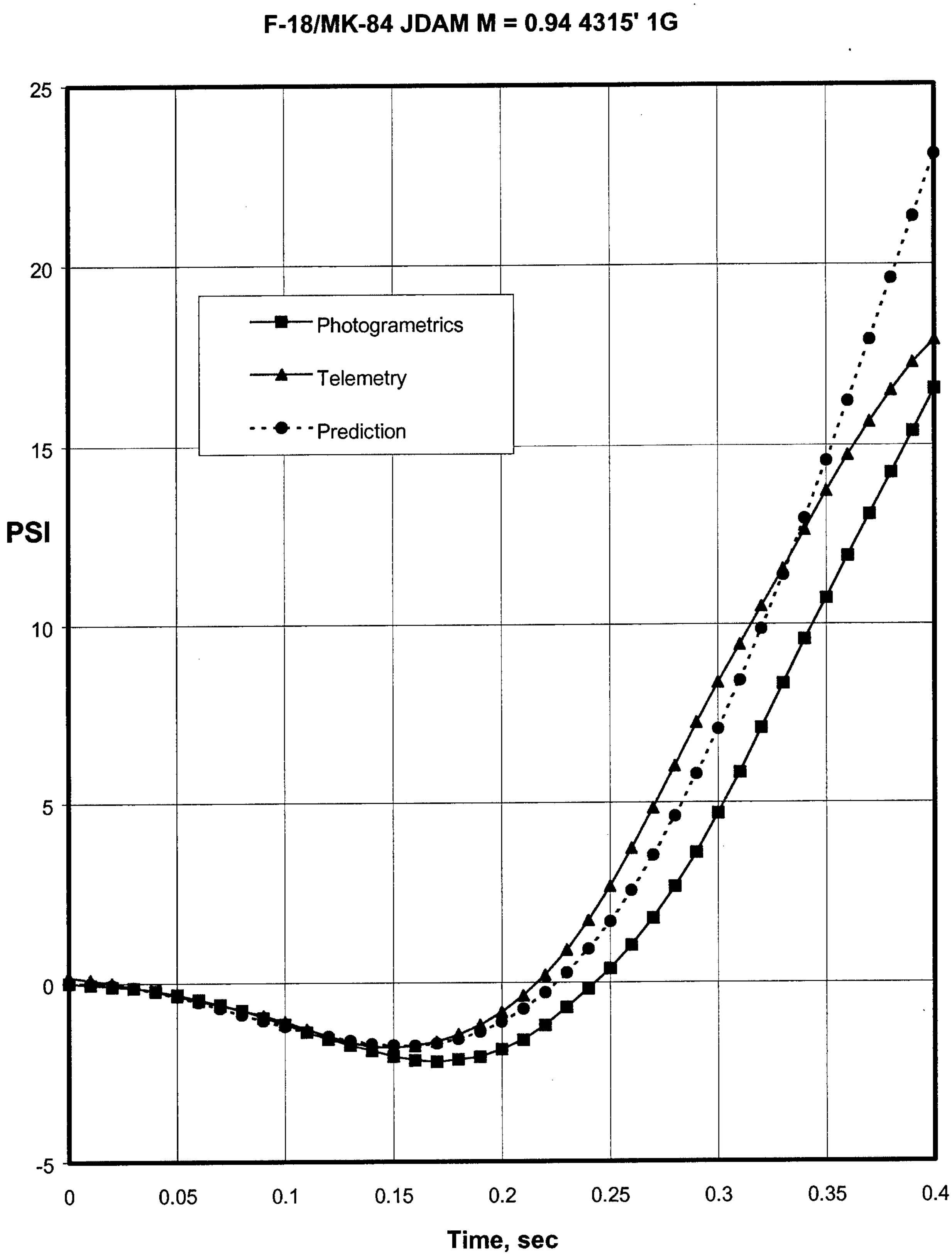

F-18/MK-84 JDAM M = 0.94 4315' 1G
PSI
Time, sec
Photogrametrics
Telemetry
Prediction
25
20
15
10
5
0
-5
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

FIGURE 6

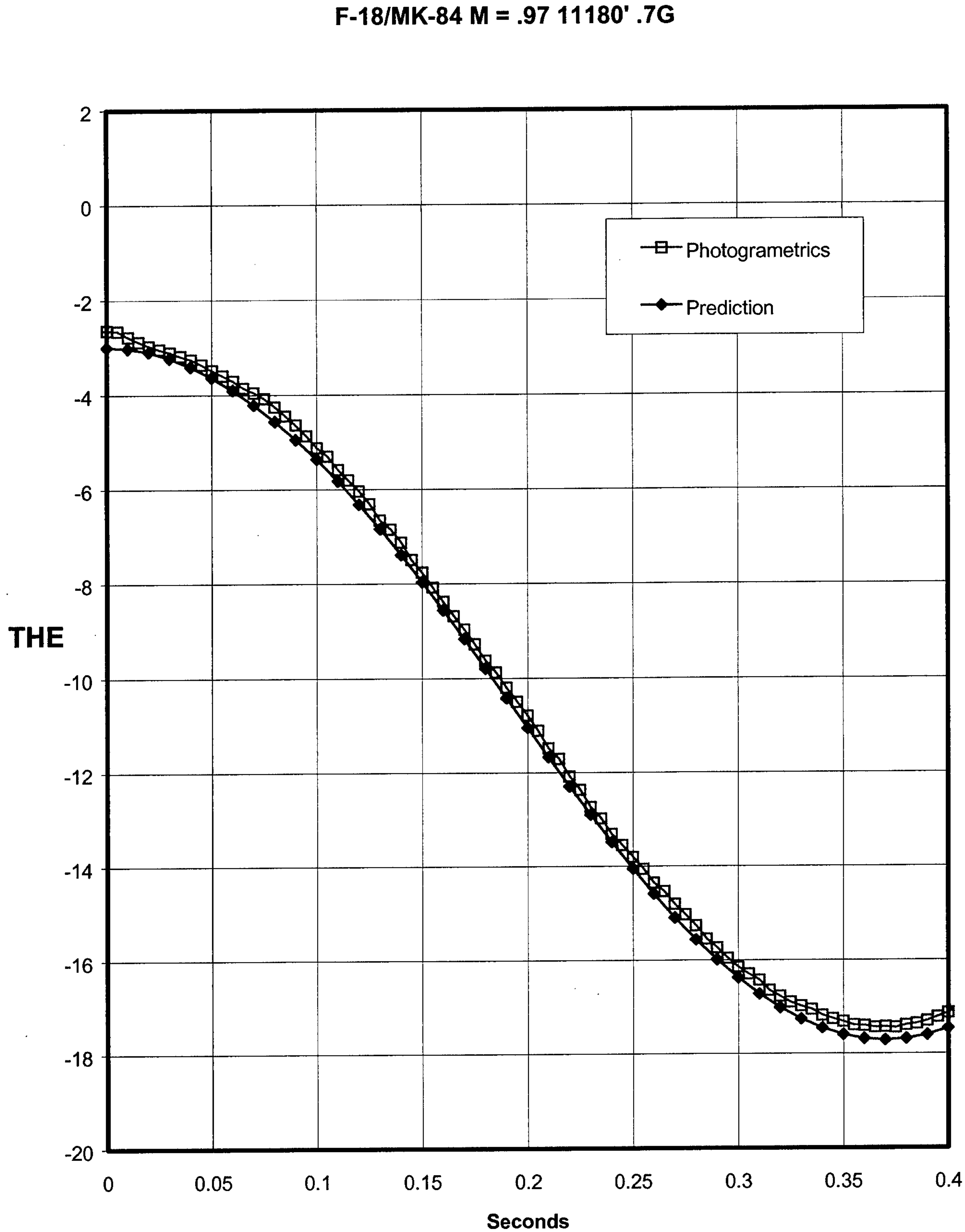

F-18/MK-84 M = .97 11180' .7G
Photogrametrics
Prediction
THE
Seconds
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

FIGURE 7

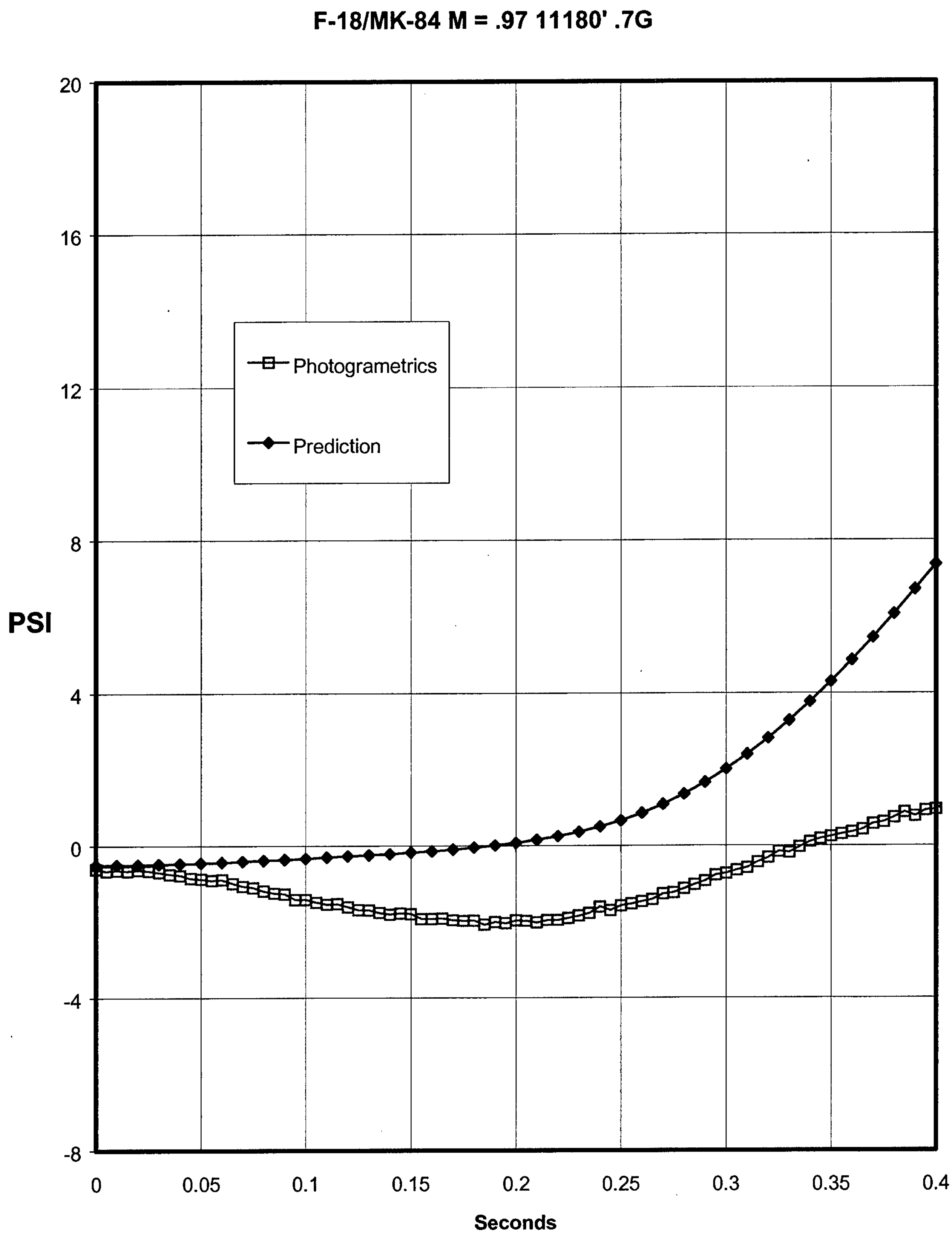

F-18/MK-84 M = .97 11180' .7G
20
16
12
8
4
0
-4
-8
PSI
Photogrametrics
Prediction
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Seconds

FIGURE 8

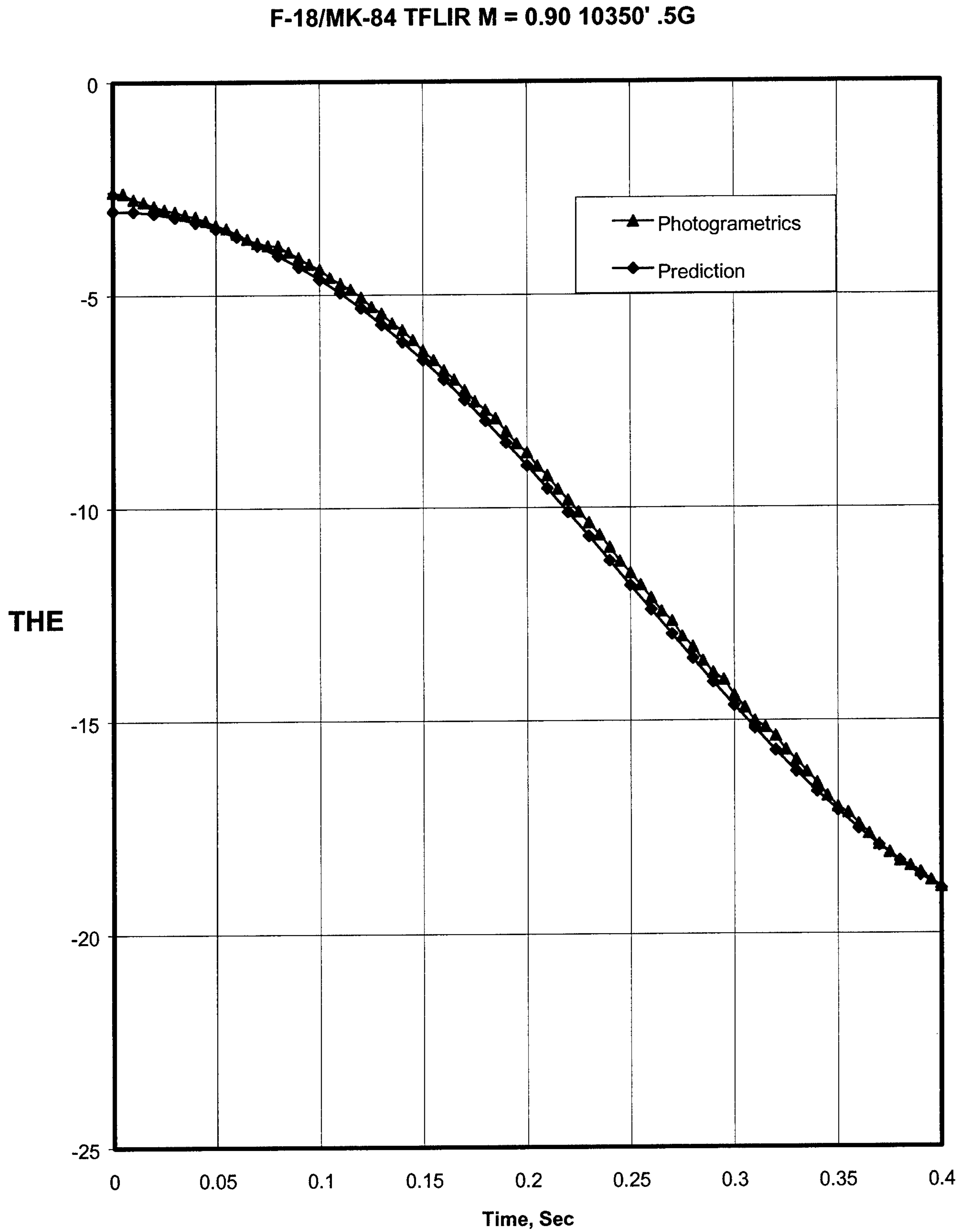

F-18/MK-84 TFLIR M = 0.90 10350' .5G
0
-5
-10
-15
-20
-25
THE
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time, Sec
Photogrametrics
Prediction

FIGURE 9

F-18/MK-84 TFLIR M = 0.90 10350' .5G

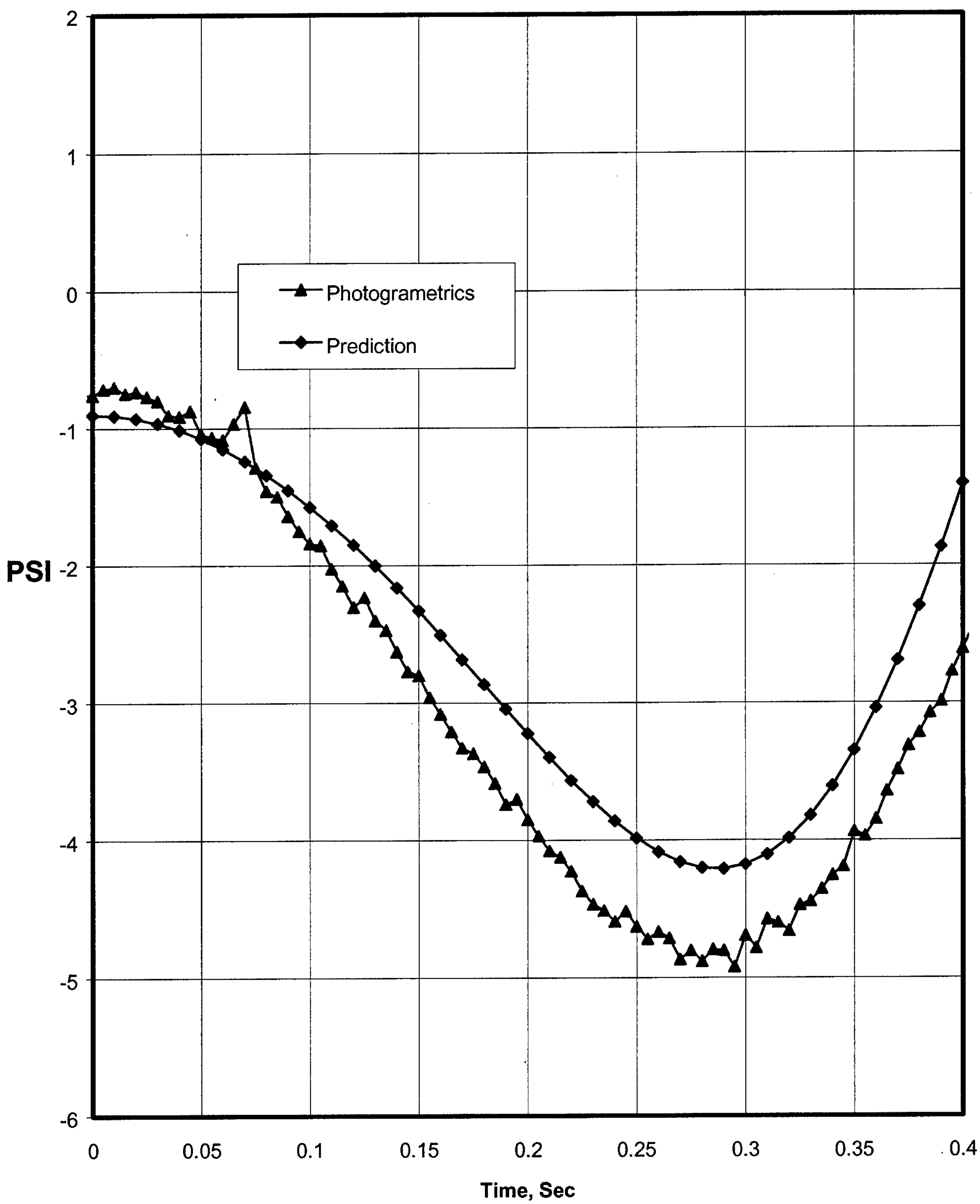


FIGURE 10

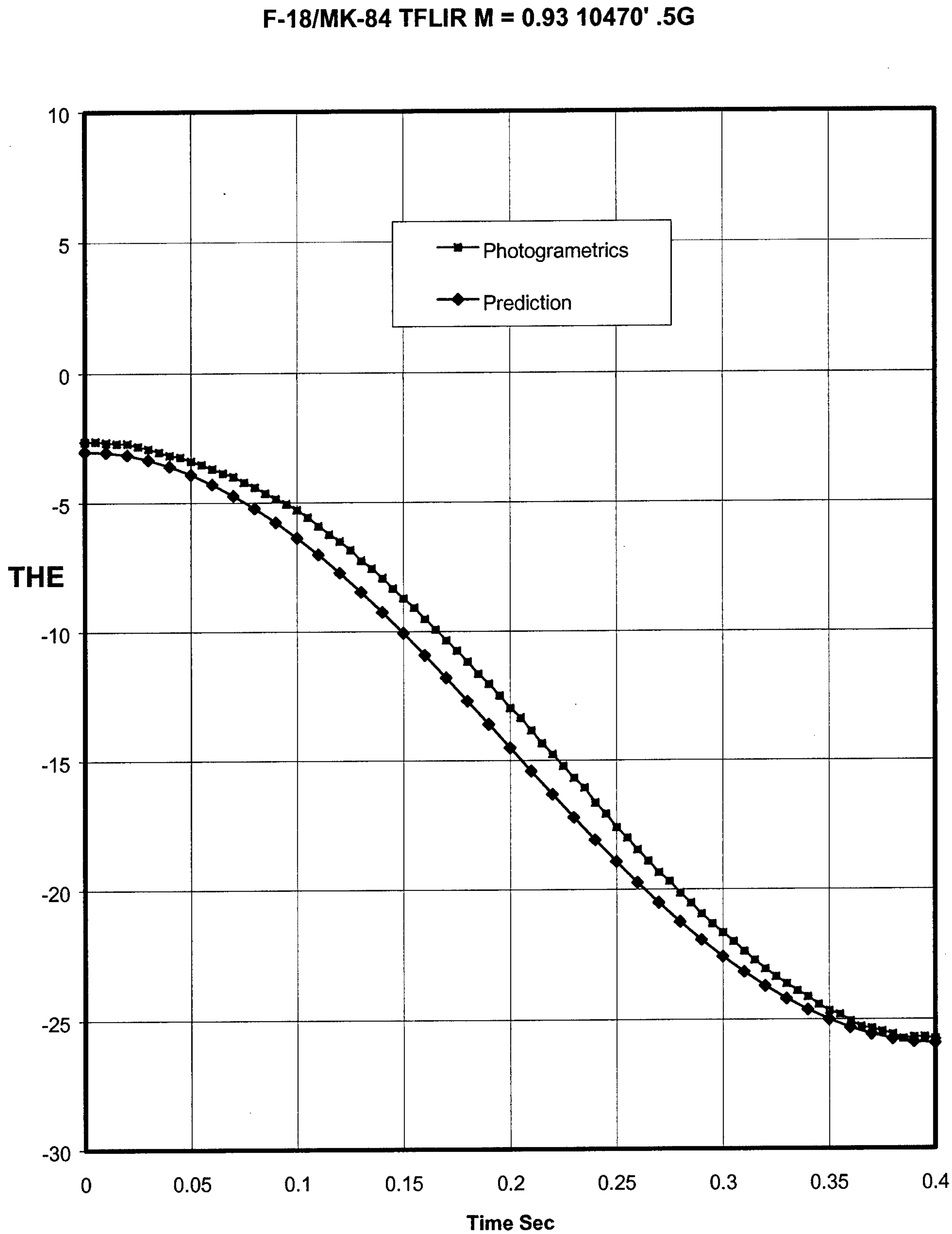

F-18/MK-84 TFLIR M = 0.93 10470' .5G
10
5
0
-5
-10
-15
-20
-25
-30
THE
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time Sec
Photogrametrics
Prediction

FIGURE 11

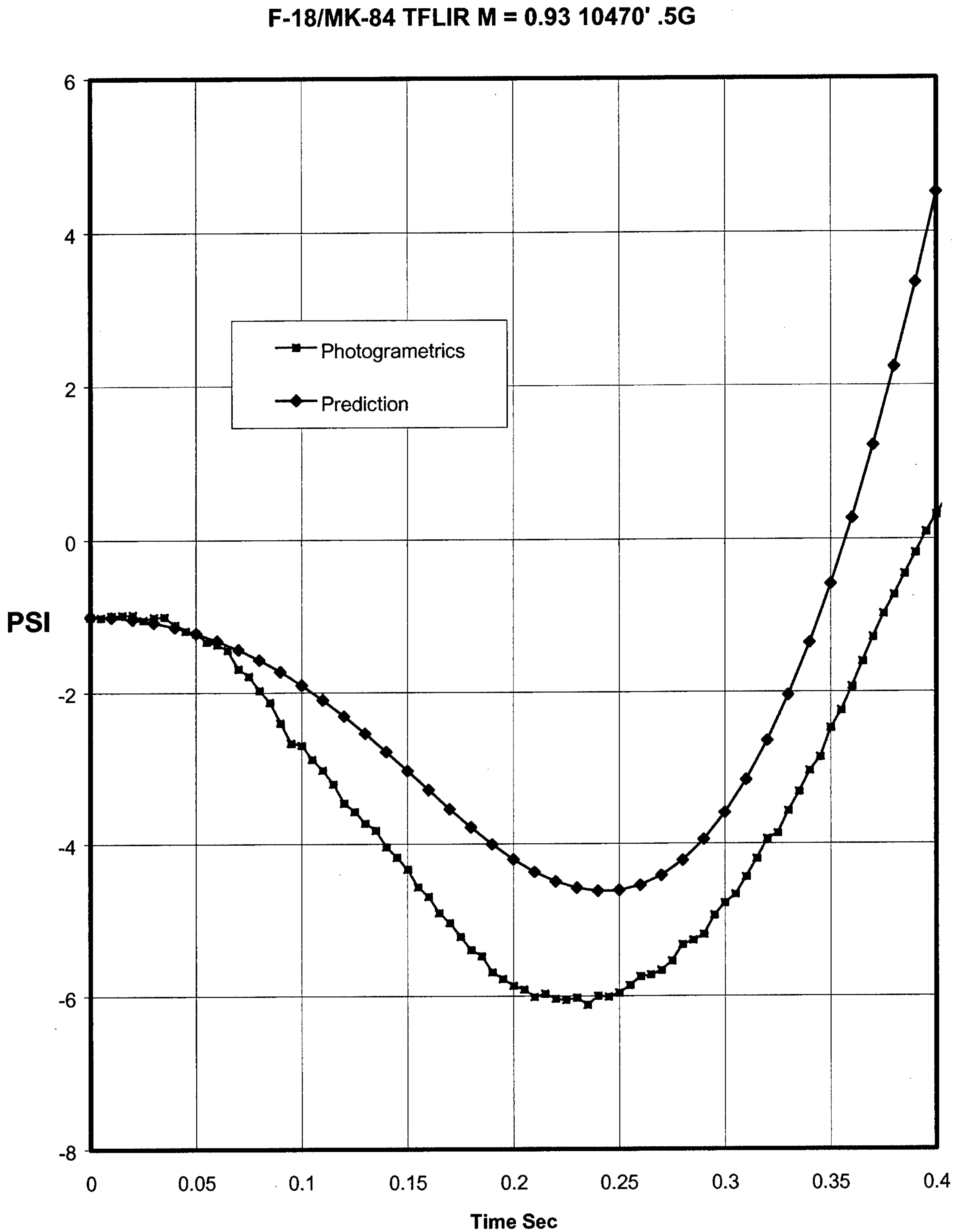

F-18/MK-84 TFLIR M = 0.93 10470' .5G
Photogrametrics
Prediction
PSI
Time Sec
6
4
2
0
-2
-4
-6
-8
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

FIGURE 12

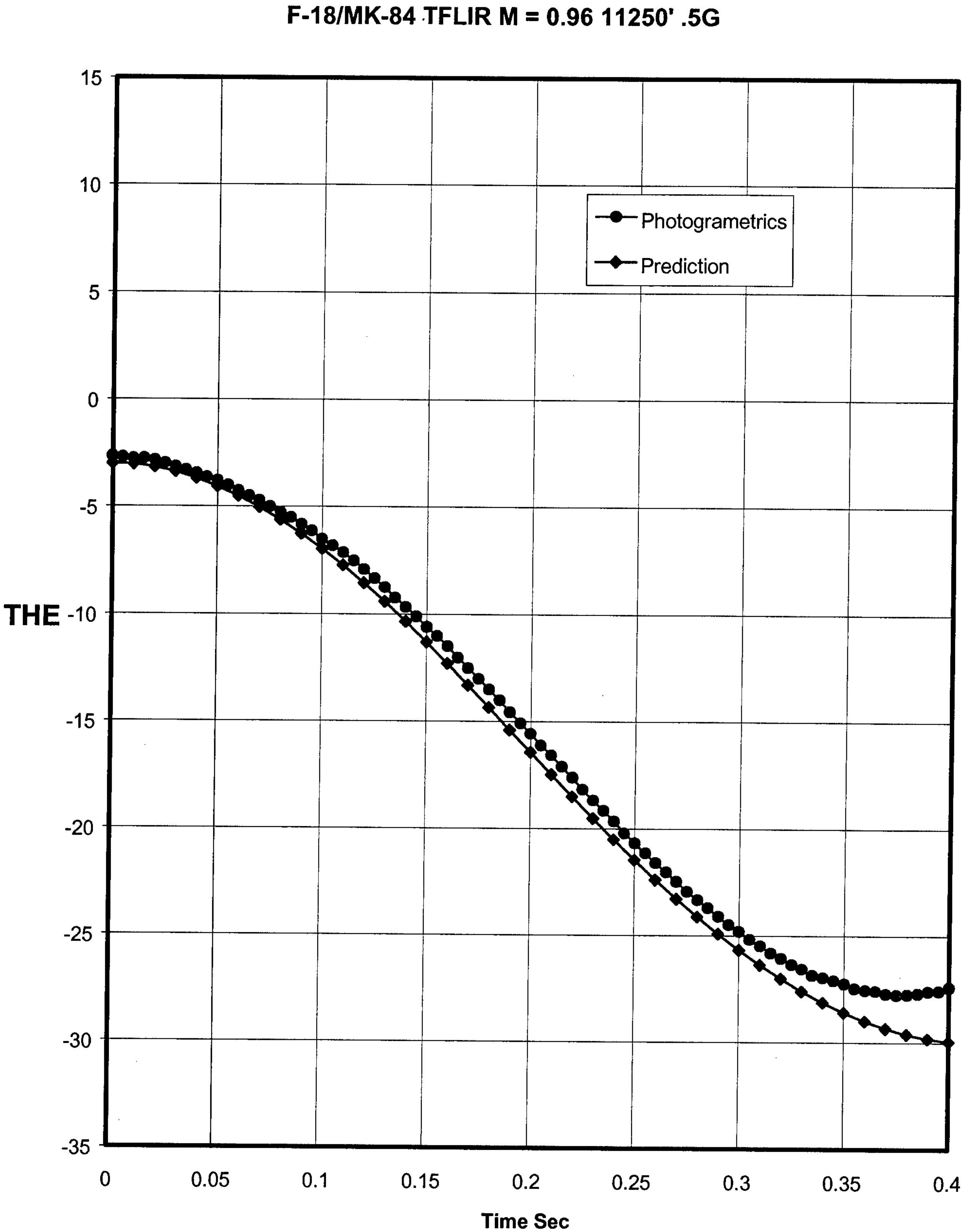
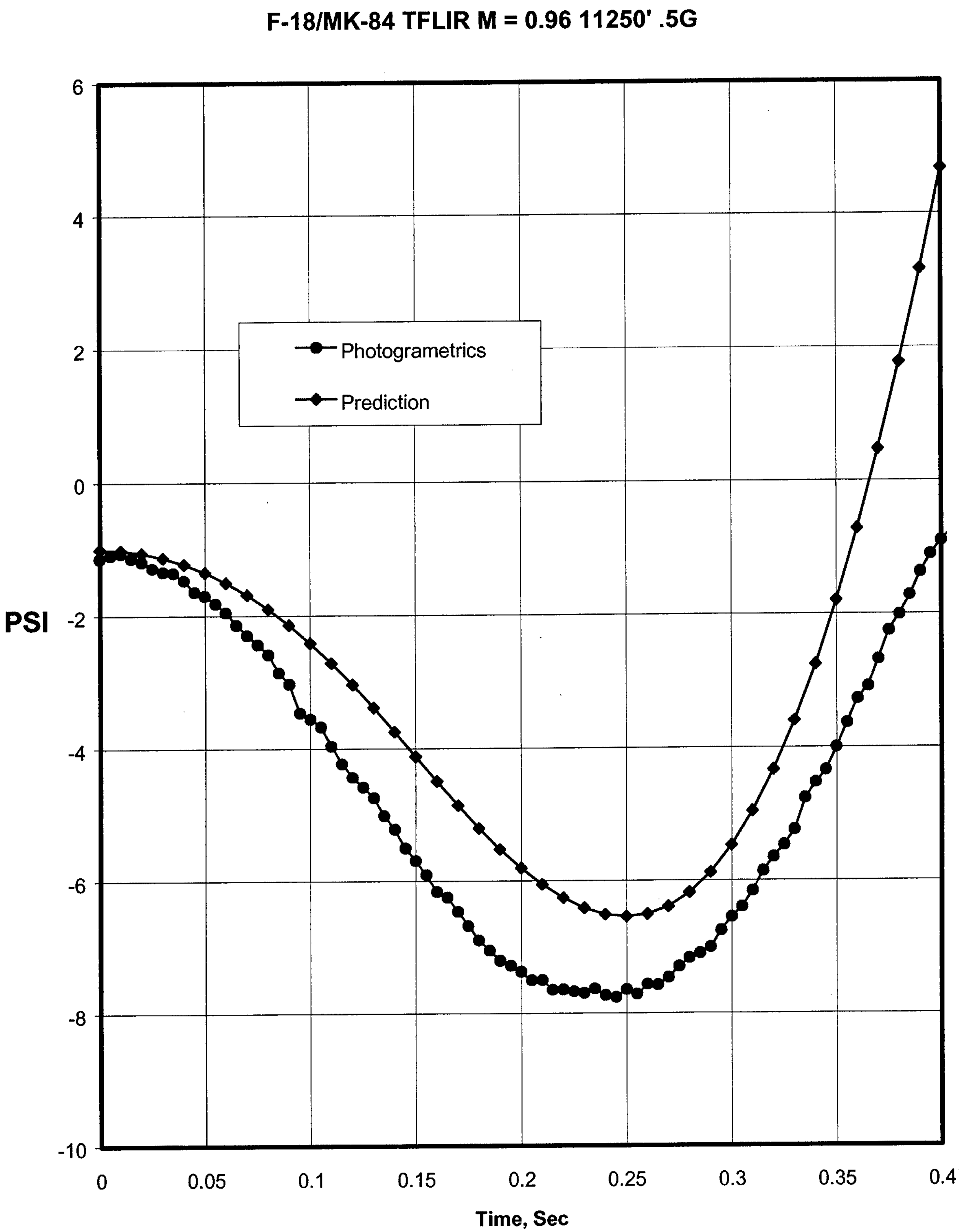
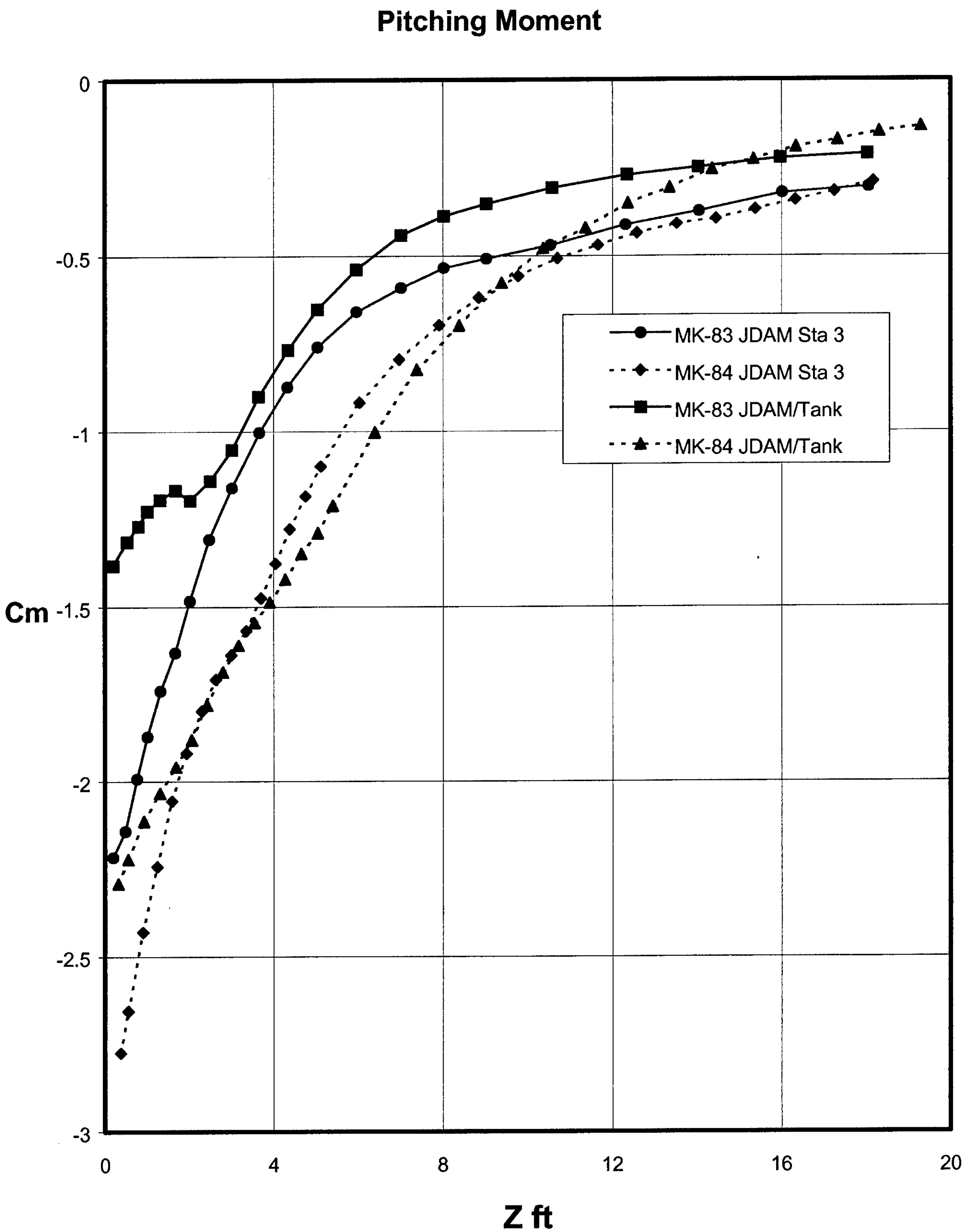

F-18/MK-84 TFLIR M = 0.96 11250' .5G
Photogrametrics
Prediction
THE
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time Sec

FIGURE 13



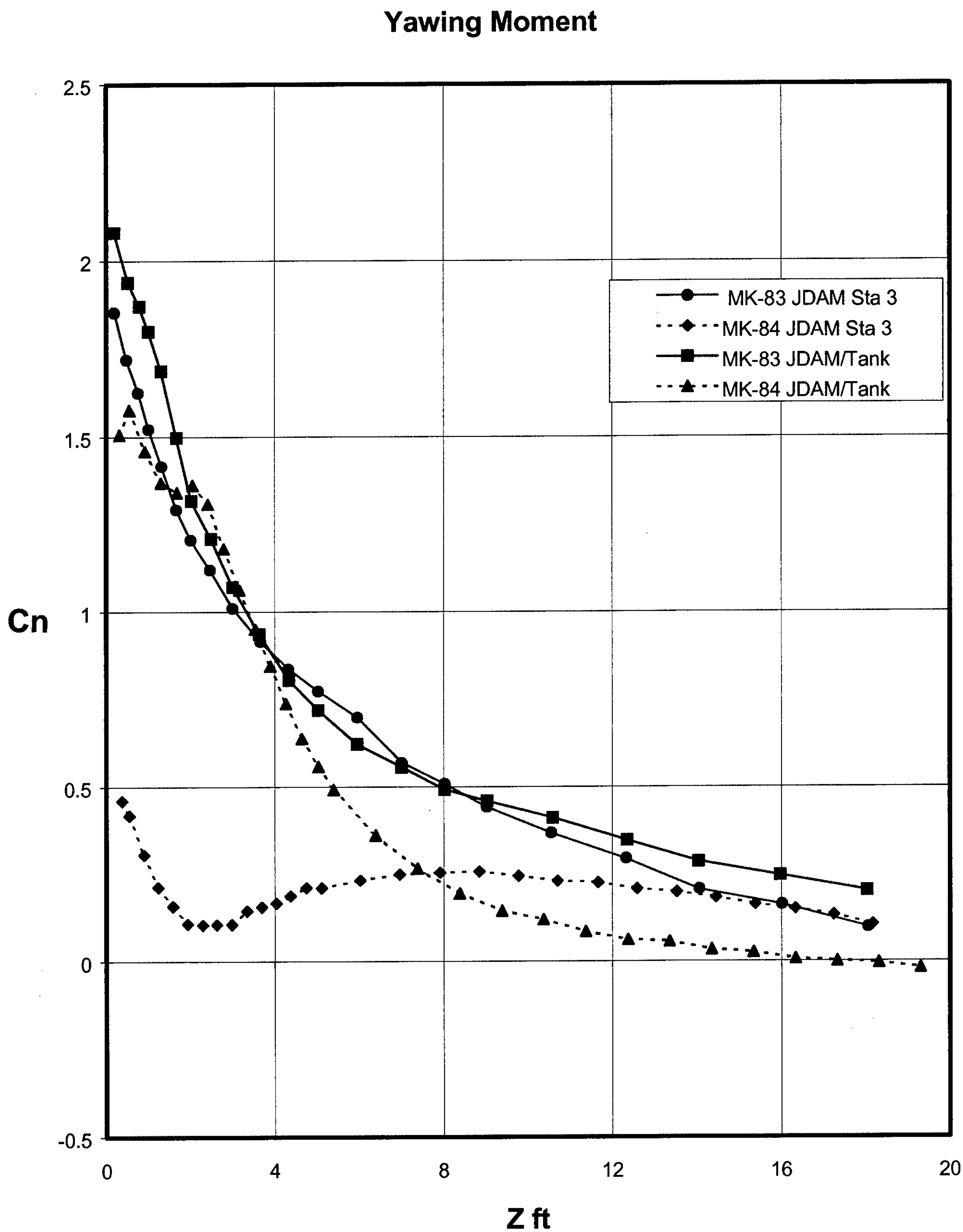
F-18/MK-84 TFLIR M = 0.96 11250' .5G
6
4
2
0
-2
-4
-6
-8
-10
PSI
Photogrametrics
Prediction
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Time, Sec

FIGURE 14



Pitching Moment
Cm
Z ft
0
-0.5
-1
-1.5
-2
-2.5
-3
0
4
8
12
16
20
MK-83 JDAM Sta 3
MK-84 JDAM Sta 3
MK-83 JDAM/Tank
MK-84 JDAM/Tank

FIGURE 15



Yawing Moment
2.5
2
1.5
1
0.5
0
-0.5
Cn
0
4
8
12
16
20
Z ft
MK-83 JDAM Sta 3
MK-84 JDAM Sta 3
MK-83 JDAM/Tank
MK-84 JDAM/Tank

FIGURE 16